Higgs induced light leptoquark-diquark mixing and proton decay

Uma Mahanta

Mehta Research Institute

Chhatnag Road, Jhusi

Allahabad-211019, India

email:mahanta@mri.ernet.in

Abstract

In low energy phenomenology to avoid the strong constraints of proton decay it is usually assumed that light (≈ 250 Gev) leptoquarks couple only to quark-lepton pairs and light diquarks couple only to quark pairs. In this paper we present two specific examples where the higgs induced mixing between leptoquarks and diquarks through trilinear interaction terms reintroduces the troublesome couplings and gives rise to proton decay. The bound on the unknown parameters of this scenario that arise from proton life time has also been derived.

Leptoquarks (LQ) [1] and diquarks (DQ) [2, 3] are colored scalar or vector particles that carry baryon numbers of $\pm\frac{1}{3}$ and $\pm\frac{2}{3}$ respectively. They occur naturally in many extensions of the standard model (SM) e.g. superstring inspired grand unified models based on $E(6)$ [3], technicolor models [2] and composite models [1] of quarks and leptons. If LQs and DQs couple both to quark-lepton pairs and quark pairs then they lead to too rapid proton decay. To be consistent with the proton life time such LQs and DQs must have a mass of the order of $(10^{12} - 10^{15})$ Gev. To avoid this strong constraint and to make them relevant for low energy phenomenology below 1 Tev it is usually assumed that LQs couple to quark-lepton pairs but not to quark pairs and DQs couple to quark pairs but not to quark-lepton pairs. However in the presence of the SM higgs doublet ϕ the low energy effective Lagrangian will also contain a trilinear Higgs-LQ-DQ interaction term. After EW symmetry breaking (EWSB) this interaction term will induce a mixing between the LQ and the DQ which reintroduces the troublesome Yukawa couplings for LQ and DQ. If the physical LQ and DQ do not have the same mass then they lead to proton decay. There can be several different kinds [1-3] of LQ's and DQ's. However in this report we shall not go into a detailed discussion of every LQ-DQ mixing that can possibly occur. Rather we shall give two give specific examples of Higgs-LQ-DQ interaction term and the mixing between the LQ and DQ that takes place after EWSB. For one particular case we have also calculated the mixing angle in terms of the dimensional coupling that measures the strength of the Higgs-LQ-DQ interaction term. Finally we have estimated the proton decay rate in terms of the unknown parameters of our scenario and have derived the constraint that the parameters of the Lagrangian must satisfy in order to be consistent with proton lifetime.

Consider the SM to be extended by a light (≈ 250 Gev) chiral leptoquark D and a light chiral diquark S with the following assignments under $SU(3)_c \times SU(2)_l \times U(1)_y$: $D \sim (3^*, 2, -\frac{1}{6})$ and $S \sim (3^*, 1, \frac{1}{3})$. The low energy effective Lagrangian of this extended scenario will contain besides the SM Lagranigian all possible renormalizable and gauge

invariant interaction terms between D, S and the SM fields. Of particular importance for this work are the Yukawa like couplings of D and S to the SM fermions given by the following Lagrangian

$$L_y = g_R \bar{l}_L d_R D + g' \epsilon_{ijk} \bar{d}_{Ri} u_{Rj}^c S_k + h.c.$$
$$= g_R(\bar{\nu}_L D_1 + \bar{e}_L D_2)d_R + g_R' \epsilon_{ijk} \bar{d}_{Ri} u_{Rj}^c S_k + h.c. \tag{1}$$

Here D_1 and D_2 are the isospin up and down components of D. i, j, k are the color indices. Note first that the leptoquark D couples only to quark-lepton pair and the diquark S couples only to quark pair which is required so that they do not lead to proton decay. Second both interaction terms are invariant under the SM gauge group $SU(3)_c \times SU(2)_l \times U(1)_y$. Finally the couplings of D and S are both chiral in nature i.e. they couple to quark fields of a particular chirality only. The Yukawa Lagrangian L_y also implies that D and S should carry baryon numbers of $-\frac{1}{3}$ and $\frac{2}{3}$ respectively so that L_y conserves baryon number. This kind of structure of the Yukawa couplings could arise depending on the gauge symmetry of the high energy theory and its chiral matter representation. Besides the Yukawa couplings the low energy Lagrangian for describing physics much below the compositeness scale or grand unified scale Λ must also contain all possible renormalizable and gauge invariant interaction terms between ϕ, D and S. In principle such interaction terms cannot be neglected. They could arise from the scalar potential of the high energy theory after the gauge symmetry of the high energy theory breaks down into $SU(3)_c \times SU(2)_l \times U(1)_y$. The gauge invariant trilinear interaction term between ϕ, D and S is given by the Lagrangian

$$L_s = k_1(D^+ \phi_c)S + h.c. = k_1 \frac{v+h}{\sqrt{2}} D_1^+ S + h.c. \tag{2}$$

Here ϕ_c is the charge conjugated Higgs doublet that gives mass to the up quarks in SM. The unknown mixing parameter k_1 carries the dimension of mass. After EW symmetry

breaking this interaction term will lead to mixing between D_1 and S. Note that D_1 and S carries the same charge and color assignments which is necessary so that they could mix after EWSB. The above higgs-LQ-DQ interaction term violates both baryon number and lepton number by one unit ($\delta B = -\delta L = 1$). Here we are implicitly assuming that the breaking of baryon number symmetry is first communicated to the scalar sector of the high energy theory which in turn communicates it to other sectors e.g the Yukawa sector. Recall that in the SM baryon number conservation is realized as an accidental global symmetry [4]. By that we mean that given the particle content and the gauge group $SU(3)_c \times SU(2)_l \times U(1)_y$ of the SM it is not possible to write a renormalizable and gauge invariant interaction term that violates baryon number. No adhoc global symmetry is required to explain the near abscence of proton decay. However as we have seen above that if we keep the gauge group the same but allow additional particles like color triplet scalars then it is possible to write down a renormalizable and gauge invariant interaction term that violates baryon number.

We shall now show that the mixing between D_1 and S induced by ϕ can lead to proton decay in the "ν + any channel" where any refers to a positively charged non-strange meson. Consider the full scalar potential involving D and S

$$V(D, S) = \mu_1^2 D^+ D + \mu_2^2 S^+ S + \lambda_1 (D^+ D)^2 + \lambda_2 (S^+ S)^2$$

$$+ \lambda_1' (D^+ D)(\phi^+ \phi) + \lambda_2' (S^+ S)(\phi^+ \phi) + (k_1 D^+ \phi_c S + h.c.) \tag{3}$$

The quartic scalar interactions are not relevant to our present work. μ_1^2 and μ_2^2 are the mass parameters associated with the gauge eigenstates D and S. After EWSB the trilinear interaction term between ϕ, D and S induces a mixing between D_1 and S. It can be shown that the eigenvalues of the mass squared matrix $M_{D_1 S}^2$ are given by

$$\lambda_+ = M_{D_1}^2 = \frac{1}{2}(\mu_1^2 + \mu_2^2) + \frac{1}{2}\sqrt{\epsilon^2 + 2k_1^2 v^2}. \tag{4a}$$

and

$$\lambda_- = M_S^2 = \frac{1}{2}(\mu_1^2 + \mu_2^2) - \frac{1}{2}\sqrt{\epsilon^2 + 2k_1^2 v^2}. \tag{4b}$$

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where $\epsilon = \mu_1^2 - \mu_2^2$. The physical states correponding to $\lambda_\pm$ are given by $D_1' = D_1 \cos\theta - S \sin\theta$ and $S' = D_1 \sin\theta + S \cos\theta$. Here $\cos\theta = \frac{\sqrt{2}k_1 v}{[2k_1^2 v^2 + (\sqrt{\epsilon^2 + 2k_1^2 v^2} - \epsilon)^2]^{\frac{1}{2}}}$.

The Yukawa couplings of the LQ and the DQ written in terms of mass eigenstates are given by

$$L_y = g_R[\bar{\nu}_L(D_1' \cos\theta + S' \sin\theta + \bar{e}_L D_2]d_R$$

$$+ \epsilon_{ijk}g_R'\bar{d}_{Ri}u_{Rj}^c[S_k' \cos\theta - D_{1k}' \sin\theta + h.c.] \tag{5}$$

. The above Yukawa Lagrangian does lead to proton decay in the "ν + any" channel via the exchange of D and S particles. The effective four fermion Lagrangian for this decay is given by

$$L_{eff} = g_R g_R' \sin\theta \cos\theta \epsilon_{ijk}(\bar{\nu}_L d_{Rk})(\bar{u}_{Rj}^c d_{Ri})(\frac{1}{M_S^2} - \frac{1}{M_D^2}) + h.c. \tag{6}$$

This is the effective Lagrangian at a scale $M^2 = M_D^2 \approx M_S^2 \approx (250 Gev)^2$. In order to use it for proton decay it has to be renormalized down to a scale $\mu^2 = (1 Gev)^2$ under the unbroken QCD and EM interactions. The EM corrections are small because the coupling itself is small. The QCD corrections are not that large either because $\ln\frac{M^2}{\mu^2}$ is not large in our case. It can be shown that the proton decay rate arising from the above effective Lagrangian is given by

$$\Gamma(p \to \nu_e + any) \approx \frac{1}{17\pi^2 R^3}G_{eff}^2 m_q^2 A^2(\frac{M}{\mu}) \tag{7}$$

.

Here $A(\frac{M}{\mu})$ includes the effects of renormalization group evolution from M to μ. We shall assume it to be of order one. $R = \frac{3}{4}$ fm, $m_q \approx \frac{1}{3}$ Gev and $G_{eff} = \frac{1}{2\sqrt{2}}g_R g_R' \sin\theta \cos\theta(\frac{1}{M_S^2} - \frac{1}{M_D^2})$. The present lower bound on $\tau(p \to \nu + any)$ is 25×10^{30} yr [5]. It is clear from the expression of G_{eff} that the tight constraint of proton lifetime can be satisfied either with $\sin\theta \ll 1$ or $\cos\theta \ll 1$. It can be shown that for $\sin\theta \ll 1$ we require $k_1 v \ll \sqrt{2}\epsilon$. On the other hand for $\cos\theta \ll 1$ we need $\sqrt{2}k_1 v \ll (\sqrt{\epsilon^2 + 2k_1^2 v^2} - \epsilon)$. For $M_S = 200$ Gev and $M_D = 300$ Gev [6] the product combination $g_R g_R' \sin\theta \cos\theta$

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must be less than 3×10^{-26} in order that the decay rate in eqn(7) is consistent with the proton lifetime. If we assume that the Yukawa couplings g_R and g'_R are of the order of .1, then for $\sin \theta \ll 1$ we must adjust the parameters of the Lagrangian so as to satisfy $k_1 v < 4 \times 10^{-24} \epsilon$. On the other hand for $\cos \theta \ll 1$ the parameters must be adjusted so as to satisfy $\sqrt{2} k_1 v < 3 \times 10^{-24} (\sqrt{\epsilon^2 + 2k_1^2 v^2} - \epsilon)$. These constraints may not be stable against radiative corrections requiring extreme fine tuning to each order in loop expansion. We would like to reiterate that there can be several different species of LQ's as well as DQ's. However the mixing between D_1 and S and hence proton decay occurs only for specific $SU(3)_c \times SU(2)_l \times U(1)_y$ assignments of the LQ and the DQ. Unless these assignments are achieved there is no mixing between the LQ and DQ and hence no contribution to proton decay.

Having shown that higgs induced mixing between the doublet leptoquark D and the singlet diquark S does lead to proton decay we shall now present another concrete example where the same phenomenon also takes place. An EW triplet diquark T_{ak} (a is the $SU(2)_l$ index and k the color index) can also mix with the doublet leptoquark D and contribute to both proton decay and neutron decay. Let the $SU(3)_c \times SU(2)_l \times U(1)_y$ assignments of T_{ak} be given by $(3, 3, -\frac{1}{3})$. The triplet diquark T_{ak} can couple to LH quark pair according to the following Lagrangian:

$$L'_y = g''_R \epsilon_{ijk} \bar{q}^c_{Li} \tau_a i \tau_2 T_{ak} + h.c.$$

$$= g''_R \epsilon_{ijk} [-\sqrt{2} \bar{u}^c_{Li} u_{Lj} T_{-k} + \sqrt{2} \bar{d}^c_{Li} d_{Lj} T_{+k} + (\bar{u}^c_{Li} d_{Lj} + \bar{d}^c_{Li} u_{Lj}) T_{0k}] \qquad (6)$$

where $T_{+k} = \frac{T_{1k} + iT_{2k}}{\sqrt{2}}$, $T_{-k} = \frac{T_{1k} - iT_{2k}}{\sqrt{2}}$ and $T_{0k} = T_{3k}$. T_{+k} and T_{-k} carry electromagnetic charges of $\frac{2}{3}$ and $-\frac{4}{3}$ units respectively. Note that T_{-k} is not the antiparticle of T_{+k} since they carry different electromagnetic charges. The gauge invariant Higgs-LQ-DQ interaction term in this case will be given by

$$L'_s = k_2 (D^+ \tau_a \phi_c) T^*_a + h.c.$$

$$= k_2 \frac{v + h}{\sqrt{2}} [D_2^+ T^*_+ + D_1^+ T^*_0 + h.c.] \qquad (7)$$

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The mixing between D_1 and T_0^* leads to $p \to \pi^+ \nu$ and the mixing between D_2 and T_+^* leads to $n \to \pi^+ e^-$ both of which violate baryon number.

The low energy effective Lagrangian will also contain trilinear Higgs-LQ-LQ and Higgs-DQ-DQ interaction terms. Afetr EWSB these terms give rise to mixing between different multiplets of LQ and DQ. Such interaction terms do not violate baryon number but they could violate lepton number. Of particular importance is the Higgs-LQ-LQ ineraction for a pair of chiral leptoquarks belonging to different weak SU(2) multiplets. The mixing between two different LQ multiplets will give rise to helicity unsuppressed contribution to $\pi^- \to e^- \bar{\nu}_e$ The helicity suppressed SM contribution to $\pi^- \to e^- \bar{\nu}_e$ is in excellent agreement with the experimental data. Therefore any helicity unsuppressed contribution arising from new physics must be strongly constrained. This leads to stringent bounds on the mixing parameter between the two LQ multiplets. The mixing between different LQ multiplets can also lead to majorana mass matrix for neutrinos. A complete discussion of these topics can be found in Ref. [7] and will not be taken up here.

To conclude in this report we have shown that the usual assumption of low energy phenomenology that LQ's couple only to q-l pairs and DQ's couple only to quark pairs is not sufficient to stabilize the proton. We have given two specific examples where the Higgs-LQ-DQ interaction term induces a mixing between the LQ and DQ after EWSB. This mixing reintroduces the troublesome couplings for the LQ and the DQ and leads to proton decay. We find that in order to be consistent with the bound on proton lifetime the parameters of the Lagrangian must either satisfy $k_1 v < 4 \times 10^{-24} \epsilon$ or $\sqrt{2} k_1 v < 3 \times 10^{-24} (\sqrt{\epsilon^2 + 2 k_1^2 v^2} - \epsilon)$. In deriving these constraints we have assumed that $g_R \approx g_R' \approx .1$, $M_{D_1} = 300$ Gev and $M_S = 200$ Gev. These constraints may not be stable against radiative corrections requiring extreme fine tuning of the parameters to each order in loop expansion. This naturalness problem can perhaps be resloved by means of some new symmetry that remains unbroken in the low energy theory and prevents the Higgs-LQ-DQ interaction term from occuring in the effective Lagrangian.

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